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Numerical Modeling of Storm Surges in Chesapeake Bay

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Abstract

This paper presents the methodology, procedures, and results of numerically modeled high water levels from selected historical tropical and extratropical storms in Chesapeake Bay. The study is a part of the effort of life-cycle storm flooding analyses to compute mean frequency relationships with standard deviation error estimates (Scheffner et al. 1999, Melby et al 2005). A regional scale hydrodynamic model ADCIRC (Luettich et al. 1992; Luettich and Westerink 2003) is used to calculate water levels under high surface winds and low atmospheric pressure associated with the passage of storms. These estimates include astronomical tides. The numerical modeling considered 86 historical tropical and extratropical storms to simulate water-surface elevations throughout Chesapeake Bay. For tropical storms, surface wind and pressure fields were generated with the Planetary Boundary Layer (PBL) model (Cardone 1977; Cardone et al. 1992), and storm tracks were from the North Atlantic tropical storm track list (http://weather.unisys.com/hurricane). For extra-tropical storms, wind fields were extracted from the long-term wind hindcast database by the Meteorological Service of Canada, formerly Atmospheric Environment Service, AES (Swail et al. 2000) and the reanalysis project database (Kalnay et al. 1996) by the U.S. National Centers for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR). The pressure fields were obtained from NCEP/NCAR database. Validation of PBL, AES, NCEP/NCAR winds, and model water levels was performed by comparing to data available at 12 NOAA meteorological stations along the perimeter of the bay. Model results show a good agreement with measured wind and water levels. A key to the successful modeling was representation of the topography of river tributaries, which flooded during the storm to contain large water storage at peak surge. Higher ground associated with major roads and highways was included in the model to protect dry plains during high water level events.

Keywords: Numerical modeling, Storm surge, Winds, Tropical and extra-tropical storms, Water levels, Frequency relations.

Mathematics Subject Classification: 62N05, 62P30, 65C20.

JEL Classification: C32, C63.

1 Introduction

The reliability of numerical storm surge estimates by regional scale hydrodynamic models depends on the accuracy of input wind and pressure fields associated with the storms as well as bathymetry and land elevation of the modeled domain. In numerical water level predictions, it is essential to adjust the computed wind field over land-water interface or over a bay. In addition, a high-resolution representation of the bathymetry and flood-prone area topography has a crucial role on accuracy and modeling of storm surges in a confined estuary.

In the present study, both surface wind and pressure fields were generated from a PBL numerical model for tropical storm events. The tropical cyclone track information was obtained from the North

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14. ABSTRACT
This paper presents the methodology, procedures, and results of numerically modeled high-water levels from 86 historical tropical and extratropical storms throughout Chesapeake Bay. The study is a part of the effort of life-cycle storm flooding analyses to compute mean frequency relationships with standard deviation error estimates. A regional scale hydrodynamic model ADCIRC is used to calculate water levels under high surface winds and low atmospheric pressure associated with the passage of storms. For tropical storms, surface wind and pressure fields were generated with the Planetary Boundary Layer (PBL) model, and storm tracks were from the North Atlantic tropical storm track list. For extratropical storms, wind fields were extracted from the long-term wind hindcast database by the Meteorological Service of Canada and the reanalysis project database by the U.S. National Centers for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR). The pressure fields were obtained from the NCEP/NCAR database. Model results show a good agreement with measured wind and water levels. A key to the successful modeling was representation of the topography of river tributaries, which flooded during the storm to contain large water storage at peak surge.

15. SUBJECT TERMS

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Atlantic Tropical Storm Track List. For extra-tropical storms, wind fields were extracted from the AES database and the reanalysis project by NCEP/NCAR. The pressure fields were obtained from the NCEP/NCAR database. Wind speeds calculated for historical storms from the PBL, AES, and NCEP/NCAR were modified over land and over the bay using procedures explained in the, *Coastal Engineering Manual* (CEM) (http://chl.erdc.usace.army.mil) by the U.S Army Corps of Engineers. Wind data measured from regional anemometers were used to develop local winds over Chesapeake Bay. The validation of PBL, AES and NCEP/NCAR winds was performed by comparing wind speed and direction at twelve NOAA meteorological stations along the perimeter of Chesapeake Bay.

The depth-integrated version of ADvanced CIRCulation (ADCIRC) model for Shelves, Coasts, and Estuaries is used for water level predictions associated with tropical and extra-tropical storms. It is based on the finite element method to solve the spatial dependence of water levels and currents in the shallow-water equations (Hench et al. 1994). The bathymetry grid was developed from several data sources, including the National Ocean Service (NOS) Digital Navigation Charts (DNC), bathymetry data from the Virginia Institute of Marine Sciences (VIMS) and GEOphysical DAta System (GEODAS), and several periodic surveys conducted in the last 5 years by the U.S. Army Corps of Engineers, Philadelphia District (NAD). The grid included the topography of river tributaries that were flooded during storms, which trapped large water storage at the peak surge. It also includes the high ground elevation along major roads and highways. The lowland topography data to +10 m elevation (referenced to mean tide level) was based on the U.S. Geological Survey Global Digital Elevation Model (DEM) database GTOPO30 (e.g., 30-sec arc resolution, http://edcdaac.usgs.gov/gtopo30/gtopo30.asp). The model validation for water levels considered two major hurricanes (Category 4-5), four moderate hurricanes (Category 2-3), and two typical northeaster storms. After the validation, the same model parameters were used to run all 86 historical tropical and extra-tropical storms that passed through the Chesapeake Bay region in the last 110 years (1895-2004).

2 Storm Selection

Eighty-six historical tropical and extra-tropical storms were selected for the Chesapeake Bay storm surge study. ADCIRC simulations of these storms provided time series of water levels and currents for each storm. Only the water level predictions were of primary interest for this study, and calculated currents were used in disposal island design studies (Dinicola et al. 2006). Forty-three hurricanes (Table 1) were selected for simulation from the North Atlantic Tropical Storm Track List (1851-2006) based on the following criteria: storms with maximum wind speeds greater than 25 m/sec (50 knots) in the area between 75 and 79 deg W longitude and 36 and 39 deg N latitude. Figure 1 shows storm tracks of the 43 hurricanes selected for this study.

Forty-three northeaster storms affecting the Bay between 1954 and 2006 were identified in the AES and NCEP/NCAR wind database. Northeaster storms were selected at the ocean entrance of the Chesapeake Bay based on criteria of peak wind speed being greater than 20 m/sec (40 knots) or 10 m/sec (20 knots) and durations exceeding 3 days. Figure 2 shows the time series of wind speed and direction of the northeasters extracted from AES data in the year 1999 at the bay entrance. In Figure 2, wind speeds above 10 m/sec are marked as black crosses, and the wind speeds of northeaster storms by green circles, and northwesters as blue circles. Table 2 presents a list of 43 northeaster storms selected for this study.

3 Adjustments to Wind and Water Levels

It is known that AES40, NCEP/NCAR and PBL model wind fields are generally accurate for the open coast and ocean applications. In the Chesapeake Bay and adjacent land areas, these wind fields have to be adjusted for the overland and over-bay effects. The adjustment applied was based on the following equation (see the CEM for details):

$$U_L = U_W/R_L$$

where U_L is the wind speed over land, U_W is the wind speed over water, and R_L is an adjustment factor. This adjustment to wind speed was made for all 86 storms following procedures described in Part II of the CEM. No adjustment to wind direction was made. Figure 3 shows an example comparison of AES 40 winds to the measured data both with and without the overland adjustment. The comparison is for September 8-15, 2003, at NOAA Station 8577330 (38°19'00"N, 76°27'12"W) during the passage of a northeaster storm. The need for adjusting the AES winds for the overland effect became more apparent with this comparison of model predictions and data.

The NOAA historical water level data (1996-2003) for Chesapeake Bay were extracted from the web site: http://tidesandcurrents.noaa.gov/, and used to determine the seasonal water level variations and validate numerical model. The data showed consistently a higher mean water level for March to November time period. Over a 8-year time frame, the average water level is approximately 0.1 m higher than the mean sea level during these months. Figure 4 shows representative monthly mean water levels in 2002 and 2003 at NOAA Stations 8574680 (Baltimore, Maryland (MD), USA) and 8638863 (Bay Bridge, Virginia (VA), USA), respectively. The figure clearly shows the presence of a seasonal variation of the mean water in the bay in the interval of March to November. Thus, an average water level increase of 0.1 m has been added to the model results (hurricanes and northeasters) to account for the seasonal variation.

4 Features of Numerical Model

The ADCIRC is an unstructured grid finite element model for calculation of tides and circulation. A successful history of accurate ADCIRC model simulations has been documented for tides (Westerink et al. 1994; Fortunato et al. 1998; Luettich et al. 1999) and for storm surge (Blain et al. 1994, 1998). As mentioned by Navon (1988), Westerink and Gray (1991), and LeRoux et al. (1998), coastal circulation models like ADCIRC using the finite element method, may contain potential errors in mass balance and spurious modes of solutions. Recent advances in computational methods, such as the use of discontinuous Galerkin method and finite volume techniques, are expected to address these problems.

ADCIRC is part of a highly developed Coastal Modeling System (CMS) that resides in the Surface-water Modeling System, SMS (Zundel et al. 1998; Zundel 2007). ADCIRC serves as the Corps of Engineers' regional oceanographic and storm surge model, and has been certified for storm surge and flooding estimates by the Federal Emergency Management Agency (FEMA). The model uses shallow-water wave equations that are formulated with hydrostatic pressure and Boussinesq approximations. The simulation of water levels and currents is discretized in space with the finite-element method and solution in time uses a predictor-corrector iterative scheme. ADCIRC can be run either as a two-dimensional depth integrated (2DDI) model or as a three-dimensional (3D) model. Nonlinear terms affecting circulation dynamics are all retained in the model governing equations.

Depending on the size of computational domain, ADCIRC can be applied either in a Cartesian or a spherical coordinate system. Specified input boundary conditions to ADCIRC include elevation (harmonic tidal constituents or time series), normal flow (harmonic tidal constituents or time series), zero normal flow, slip or no slip conditions for velocity, surface stress (wind and/or wave radiation stress), atmospheric pressure, and outward Sommerfeld wave radiation condition. The model may be forced with elevation, normal flow, surface stress boundary conditions, and tidal potential. Global-scale ADCIRC studies have been completed to provide accurate tidal constituents for the Atlantic Ocean coast, Gulf of Mexico coast, and Pacific Ocean coast of the United States. These ADCIRC tide databases (Mukai et al. 2002; Spargo et al. 2004) furnish reliable tidal constituents for project-scale simulations.

5 Grid Development

A regional scale ADCIRC grid was developed for the Coastal Inlets Research Program (CIRP) (http://cirp.wes.army.mil/cirp/cirp.html), with a coarse representation of Virginia and Maryland coasts. This grid was refined in Chesapeake Bay (Figure 5) using the NOS/DNC data, a composite dataset from VIMS, GEODAS, and periodic surveys of the Chesapeake & Delaware Canal conducted by the U.S. Army Corps o Engineers, Baltimore District, in the last 5 years. The grid was further modified to incorporate small tributaries for improved water level prediction in relatively narrow branches of the bay. It was refined to include low land topography data to +10 m elevation (referenced to mean tide level) based on USGS GTOPO30, using a 30-sec arc resolution. The final grid was constructed for a minimum resolution of 50 m in shallow water areas in the bay and a maximum element size of 500 m in the open ocean. The numerical grid was developed to represent the present bay condition.

6 Model Validation

ADCIRC was used with its default parameters, and no additional calibration was performed. The validation of tropical storm simulations using the PBL wind and pressure fields involved comparing measured water levels at twelve NOAA stations (Figure 6) to predicted water levels for two major hurricanes (Fran in 1996 and Isabel in 2003) and four moderate hurricanes (Bertha in 1996, Bonnie and Earl in 1998, and Floyd in 1999). These are most recent hurricanes affecting the bay for which water level data are available. Fran and Isabel approached the bay from the ocean with similar storm tracks that were nearly perpendicular to the coastline and made landfall south of the bay. They continued in a northwest course after landfall, moving farther inland toward the west of the bay. The passage of Bertha was similar to Floyd such that both hurricanes approached and passed the bay in parallel tracks along the coastline to the east of the bay. Bonnie and Earl followed a northeast track from land to ocean, crossing the coastline south of the bay. In general, hurricanes with tracks similar to Fran and Isabel have generated higher storm surge, with their onshore winds trapping more water along the coastline and in the bay.

Figure 7 shows the measured and modeled water level time series at seven NOAA stations for Hurricane Fran. Model results generally agree well with the measured water levels. At Station 8574680 (Baltimore, MD, USA) near the north end of the bay, both measured and calculated peak water levels are 1.3 m. At Station 8638863 (Bay Bridge Tunnel, VA, USA) close to the bay entrance, both measured and calculated peak water levels are 0.8 m. Figure 8 shows comparison of the measured and modeled water level time series at seven stations for Hurricane Isabel. Good agreement is seen at Station 8574680 (Baltimore, MD, USA), where measured and calculated peak

water levels are 2.2 and 2.3 m, respectively. At Station 8638863 (Bay Bridge Tunnel, VA, USA), both measured and calculated peak water levels are 1.9 m. Tables 3 to 8 provide comparison between measured and calculated peak water levels for Hurricanes Bertha, Fran, Bonnie, Earl, Floyd, and Isabel. For these hurricanes, the percent error in the predicted peak water level, defined as (predicted-measured)/measured, is between -24 to 71 percent. The root-mean-square error of the predicted peak water level normalized by the mean measured data is between 6.5 to 18.2 percent. Model water levels are generally more reliable for hurricanes of similar track to Fran and Isabel than those having storm track similar to Bertha and Bonnie, in terms comparison with the measured data.

The validation for the extra-tropical (northeaster) storm simulations was similar to the validation for tropical storms. For northeasters, as the wind blows steadily from north to south, the water level in the south bay is higher than the north bay during flood tides. The storm surge produced under northeasters is comparatively smaller than hurricane events because of the relatively weaker wind associated with northeasters. Figure 9 shows two examples of comparison between model simulations and measurements for two typical northeasters first occurring in May 12-14, 1998, and second in September 10-12, 2003. The measurements in September 2003 include a high storm surge on September 19, induced by Hurricane Isabel. The storm surge of Isabel was simulated earlier in the study as part of model validation for tropical storms. With an adjustment of 0.1 m for average seasonal water level variation in March to November, the predicted water levels for extra-tropical storms agreed well with data. For instance, during the extra-tropical storm occurring in the mid of May 1998, the measured and calculated peak water levels at Station 8574680 (Baltimore, MD, USA) are 0.76 and 0.64 m, respectively. At Station 8638863 (Bay Bridge, VA, USA), the measured and calculated peak water levels are 1.1 and 1.2 m, respectively. During the extra-tropical storm around the 10th of September 2003, the measured and model water levels at Station 8574680 are 0.53 and 0.46 m, respectively. At Station 8638863, both measured and calculated peak water levels are 1.0 m. These comparisons indicate higher storm surge elevation occurrence in the south bay.

7 Calculated Maximum Water Levels

The calculated maximum water levels have been used different ways in projects. For the island restoration projects in the Mid-Chesapeake Bay, the results from the present study are shown in Figures 10 to 12 for Barren Island (38º19’48”N, 76º16’48”W), James Island (38º31’12”N, 76º22’12”W) and Poplar Island (38º46’12”N, 76º24’00”W). Using these values, the return period estimates can be made for the life-cycle analysis and engineering design, etc. For storm surge and flood mapping studies, the calculated maximum water levels were developed for individual storms and for all storms over the entire bay. For example, Figure 13 shows the absolute maximum water levels calculated for Hurricane Isabel. In this event, higher water levels occurred at the western side bay particularly in the southwest tributaries. Figures 14 and 15 show the overall maximum water levels from all storms simulated in the present study for hurricanes and northeasters, respectively. For hurricanes, the largest storm surge levels occur at the east side bay and low-lying islands and at the southwest side bay in the tributaries, where water is pushed and trapped at these locations. The largest storm surge levels are normally generated by stronger hurricanes (Category 3 and above) with a south-to-north track passing the bay (e.g., Hazel in 1954, Connie in 1955, and Isabel in 2003). For northeasters, higher water levels occur in the south bay as water driven southward by storms encounters flood tides entering the bay from the Atlantic Ocean. Outside the bay along the coast and in the Delaware Bay, the ocean tides contribute to the water levels more than the northeasters.

8 Summary

The U.S. Army Corps of Engineers is conducting life-cycle analysis for flood studies in the Chesapeake Bay. Numerical simulations of 86 tropical and extra-tropical storms were conducted to develop estimates of water levels in the entire Bay. These simulations were calibrated with available wind and water level data to predict extreme water levels for major tropical and sub-tropical storms occurring in the bay in the last 110 years. Calculated results overall compare well with measured winds and water levels. The difference between predicted and measured peak water levels ranged between -0.31 to 0.36 m. The largest errors were at Lewes, DE, USA, and Sewells Point, VA, USA. These differences may be attributed to a number of factors including inaccuracies in bathymetry, grid resolution, and input wind fields particularly at greater distances from storm tracks. Overall, modeling predictions and data agreed well. A key to the successful modeling was the representation of topography for river tributaries, which flooded during storms and contained large water storage at peak surge. Model water levels for hurricanes with similar track to Fran and Isabel had smaller errors of as compared to the measured data than those with storm tracks similar to hurricanes Bertha and Bonnie. The reason for this difference was that hurricanes Isabel and Fran tracked along the main axis of the bay. In contrast, hurricanes Bertha and Bonnie skirted away from the bay, leaving the bay on the weaker side of these hurricanes' path.

The largest maximum water level calculated for all 43 hurricanes in the bay was 9.4 m (Hurricane Hazel) occurring near the NOAA Station 8571892 (Cambridge, Choptank River, MD, USA). The largest maximum water level for all 43 northeasters was 2.05 m and it occurred near Station 8638610 (Sewells Pt, VA, USA). Clearly, the storm surge levels for hurricanes are much higher as compared to northeasters in the Chesapeake Bay.

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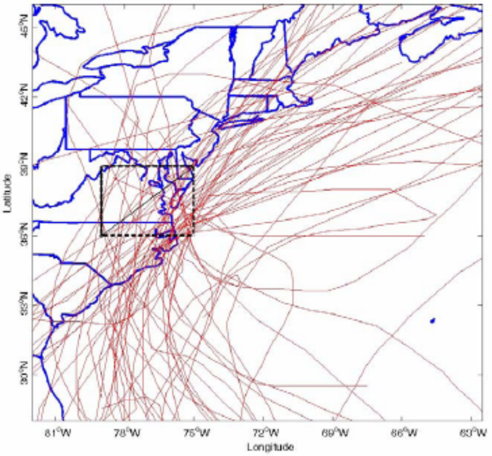

Figure 1: Tracks of 43 hurricanes (1895-2004) and a rectangle window (dash-line) used for the storm selection.

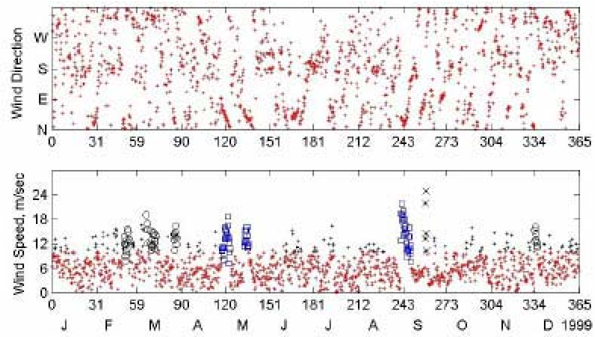

Figure 2: Screened wind events for northeasters (open square), northwesters (open circle) and hurricane wind speed (x), January to December, 1999.

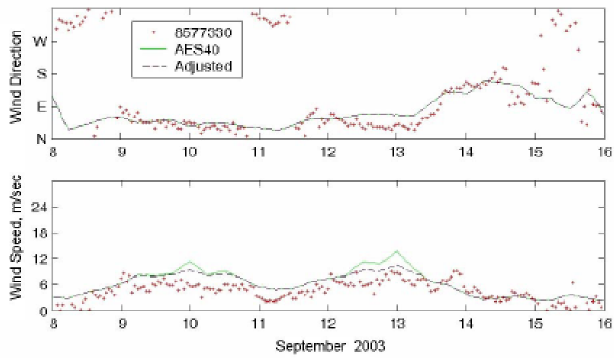

Figure 3: Comparison of AES40 winds with (dash line) and without (solid line) overland effect with measured data (cross) at NOAA Station 8577330 for September 8-15, 2003.

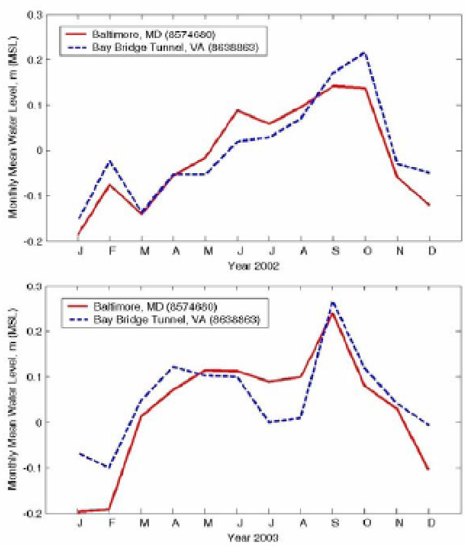

Figure 4: Monthly mean water levels at Stations 8574680 and 8638863 for 2002-2003.

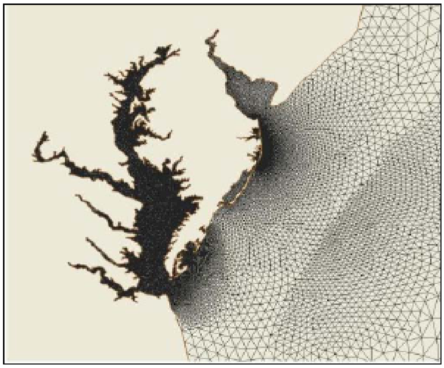

Figure 5: Portion revised ADCIRC grid resolution and shoreline.

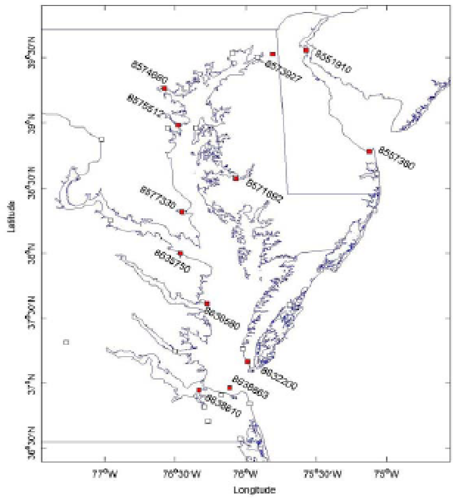

Figure 6: Wind/water level stations – active (solid square), historical (open square).

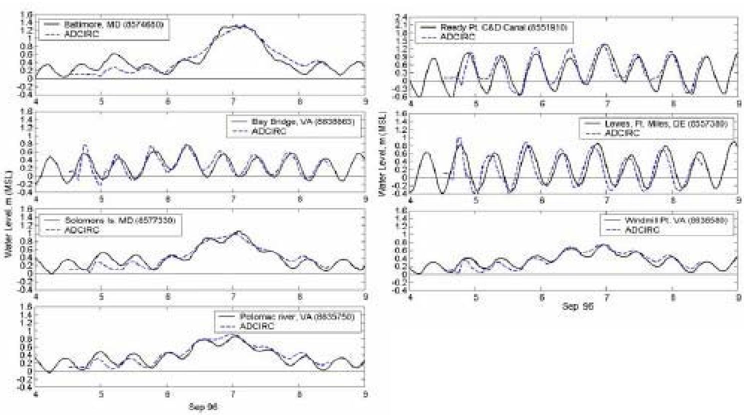

Figure 7: Measured and model water levels at seven NOAA stations during Hurricane Fran, September 4-9, 1996.

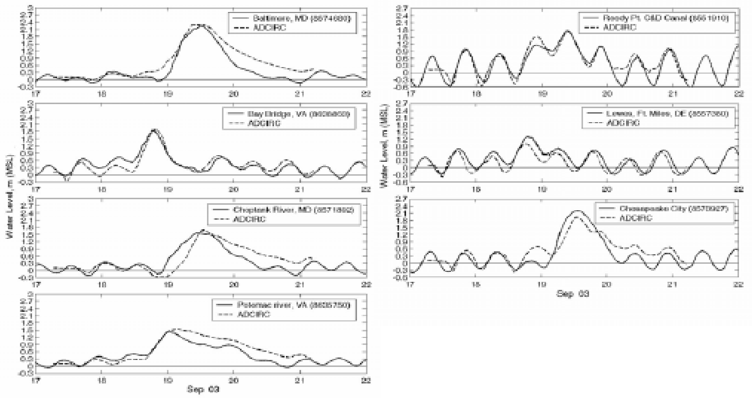

Figure 8: Measured and model water levels at seven NOAA stations during Hurricane Isabel, September 17-22, 2003.

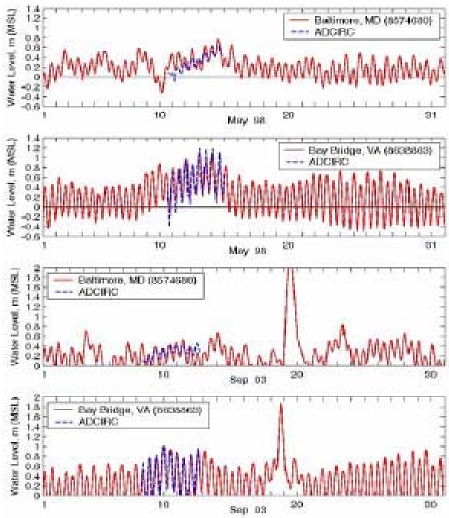

Figure 9: Measured and model water levels at Stations 8574680 and 8638863 for May 1998 and September 2003.

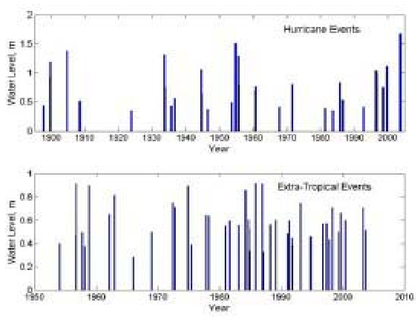

Figure 10: Calculated maximum water levels for individual storms at Barren Island.

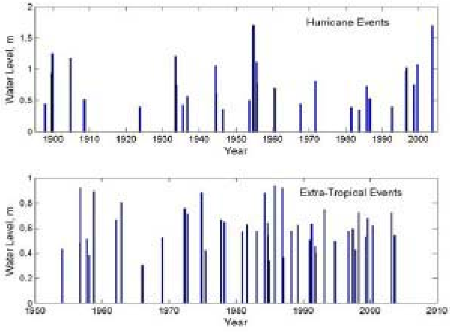

Figure 11: Calculated maximum water levels for individual storms at James Island.

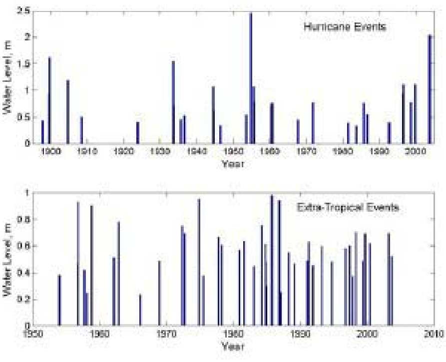

Figure 12: Calculated maximum water levels for individual storms at Poplar Island.

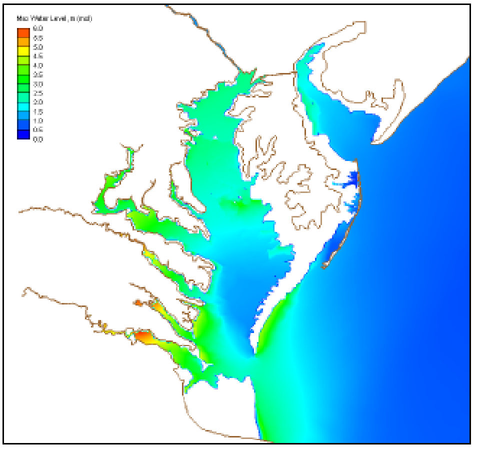

Figure 13: Calculated maximum water levels for Hurricane Isabel.

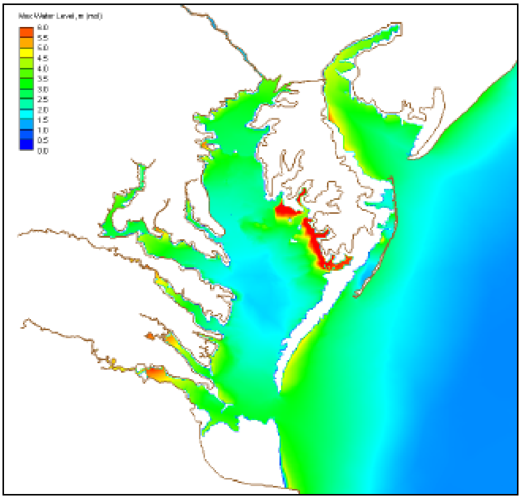

Figure 14: Calculated maximum water levels for all simulated hurricanes (1895-2004).

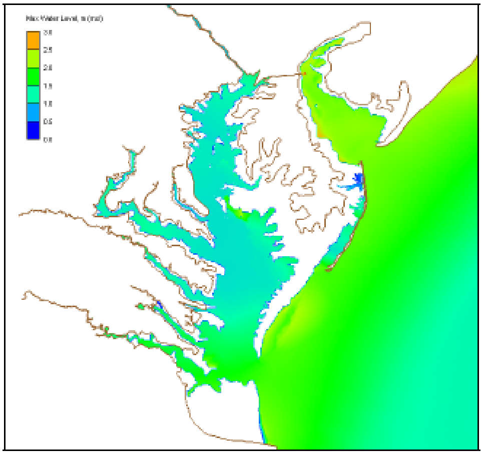

Figure 15: Calculated maximum water levels for all simulated northeasters (1954-2006).

Table 1. Selected tropical storms (hurricanes).

Storm No.	Year/ Month	Name	Database Number
1	1897/Oct	None	336
2	1899/Aug	None	347
3	1899/Oct	None	351
4	1904/Sep	None	384
5	1908/Jul	None	409
6	1923/Oct	None	492
7	1928/Sep	None	527
8	1933/Aug	None	562
9	1933/Sep	None	567
10	1934/Jun	None	577
11	1935/Aug	None	588
12	1936/Sep	None	605
13	1944/Jul	None	667
14	1944/Sep	None	671
15	1945/Sep	None	684
16	1946/Jul	None	688
17	1951/Sep	How	744
18	1952/Aug	Able	748
19	1953/Aug	Barbara	755
20	1954/Oct	Hazel	776
21	1955/Aug	Connie	780
22	1955/Aug	Diane	781
23	1955/Sep	Ione	787
24	1960/Jul	Brenda	830
25	1960/Aug	Donna	832
26	1964/Aug	Dora	865
27	1967/Sep	Doria	892
28	1971/Aug	Doria	937
29	1972/Jun	Agnes	947
30	1977/Sep	Faye	977
31	1981/Jun	Bret	1030
32	1983/Sep	Dean	1050
33	1985/Sep	Gloria	1070
34	1986/Aug	Charley	1077
35	1992/Sep	Danielle	1137
36	1995/Aug	Felix	1160
37	1996/Jul	Bertha	1175
38	1996/Aug	Fran	1179
39	1996/Oct	Josephine	1183
40	1998/Aug	Bonnie	1196
41	1998/Aug	Earl	1199
42	1999/Sep	Floyd	1214
43	2003/Sep	Isabel	1264

Table 2. Extra-tropical storms (northeasters).

Storm No.	Year/Month Date/Hour	Duration (day)	Mean Wind Speed (m/sec)
1	1954/01/21/12	2.5	18.4
2	1956/10/16/06	3.5	11.7
3	1956/10/24/06	6.5	14.3
4	1957/10/02/06	4.0	13.7
5	1958/02/15/12	6.0	14.9
6	1958/10/19/12	3.0	16.7
7	1962/03/05/06	3.0	16.3
8	1962/11/26/00	9.5	14.5
9	1966/01/26/06	6.0	15.8
10	1969/01/19/18	3.0	12.5
11	1972/05/24/00	4.0	14.0
12	1972/10/04/06	4.5	13.0
13	1974/11/30/18	4.5	14.6
14	1975/06/28/18	3.5	14.8
15	1977/10/29/00	5.0	12.4
16	1978/04/26/00	2.5	14.7
17	1980/12/26/18	5.0	13.2
18	1981/08/19/00	4.5	12.3
19	1983/02/10/18	5.0	13.4
20	1884/03/28/12	3.0	15.8
21	1884/09/26/12	6.0	13.1
22	1884/10/10/12	4.5	14.8
23	1884/11/19/06	3.5	13.0
24	1985/10/28/12	9.0	13.6
25	1986/11/29/18	4.5	12.8
26	1987/02/15/00	3.5	12.8
27	1988/04/11/12	3.0	14.8
28	1989/03/07/06	4.0	13.6
29	1991/01/07/00	5.0	13.4
30	1991/04/18/00	3.5	14.4
31	1991/10/28/00	4.0	14.6
32	1991/11/08/00	2.5	18.2
33	1993/03/12/12	3.0	13.8
34	1994/10/12/00	4.5	13.1
35	1996/10/03/12	6.5	12.4
36	1997/06/01/00	7.0	12.0
37	1997/10/14/06	7.0	12.1
38	1998/05/10/12	4.5	12.2
39	1999/04/28/12	6.0	12.5
40	1999/08/29/12	8.5	14.2
41	2000/05/28/12	3.5	15.0
42	2003/04/08/00	4.5	12.1
43	2003/09/08/06	4.5	13.9

Table 3. Comparison of data and calculated peak water levels during Bertha (July 1996).

Station No.	Station Name	Data (m)	Model (m)	Percent Error (%)
8551910	Reedy Pt, C&D Canal, DE	1.33	1.37	3.0
8557380	Lewes, Ft. Miles, DE	0.84	0.89	6.0
8574680	Baltimore, MD	0.57	0.70	22.8
8575512	US Naval Academy, MD	0.55	0.78	41.8
8577330	Solomons Is, MD	0.64	0.90	40.6
8632200	Kiptopeke Beach, VA	0.59	0.54	-8.5
8635750	Lewisetta, Potomac River, VA	0.60	0.83	38.3
8638610	Sewells Pt, VA	0.60	0.57	-5.0
8638863	Chesapeake Bay Bridge Tunnel, VA	0.60	0.66	10.0
Root-mean-square error of predicted peak water level / mean measured peak water level = 15.6%.				

Table 4. Comparison of data and calculated peak water levels during Fran (September 1996).

Station No.	Station Name	Data (m)	Model (m)	Percent Error (%)
8551910	Reedy Pt, C&D Canal, DE	1.39	1.34	-3.6
8557380	Lewes, Ft. Miles, DE	0.86	1.00	16.3
8574680	Baltimore, MD	1.33	1.30	-2.3
8577330	Solomons Is, MD	1.05	0.99	-5.7
8635750	Lewisetta, Potomac River, VA	0.87	0.93	6.9
8636580	Windmill Pt, VA	0.74	0.74	0.0
8638863	Chesapeake Bay Bridge Tunnel, VA	0.76	0.79	4.0
Root-mean-square error of predicted peak water level / mean measured peak water level = 6.5%.				

Table 5. Comparison of data and calculated peak water levels during Bonnie (August 1998).

Station No.	Station Name	Data (m)	Model (m)	Percent Error (%)
8551910	Reedy Pt, C&D Canal, DE	0.85	1.10	29.4
8557380	Lewes, Ft. Miles, DE	0.92	0.76	-17.4
8571892	Cambridge, Choptank River, MD	0.60	0.62	3.3
8574680	Baltimore, MD	0.62	0.63	1.6
8577330	Solomons Is, MD	0.57	0.67	17.5
8635750	Lewisetta, Potomac River, VA	0.65	0.78	20.0
8636580	Windmill Pt, VA	0.75	0.81	8.0
8638863	Chesapeake Bay Bridge Tunnel, VA	1.23	1.02	-17.1
Root-mean-square error of predicted peak water level / mean measured peak water level = 18.2%.				

Table 6. Comparison of data and calculated peak water levels during Earl (September 1998).

Station No.	Station Name	Data (m)	Model (m)	Percent Error (%)
8551910	Reedy Pt, C&D Canal, DE	1.18	1.25	5.9
8557380	Lewes, Ft. Miles, DE	1.13	0.89	-21.2
8571892	Cambridge, Choptank River, MD	0.64	0.54	-15.6
8574680	Baltimore, MD	0.58	0.44	-24.1
8577330	Solomons Is, MD	0.54	0.42	-22.2
8635750	Lewisetta, Potomac River, VA	0.53	0.44	-17.0
8636580	Windmill Pt, VA	0.51	0.45	-11.8
8638863	Chesapeake Bay Bridge Tunnel, VA	0.81	0.72	-11.1
Root-mean-square error of predicted peak water level / mean measured peak water level = 10.9%.				

Table 7. Comparison of data and calculated peak water levels during Floyd (September, 1999).

Station No.	Station Name	Data (m)	Model (m)	Percent Error (%)
8551910	Reedy Pt, C&D Canal, DE	1.31	1.56	19.1
8557380	Lewes, Ft. Miles, DE	1.27	1.40	10.2
8571892	Cambridge, Choptank River, MD	0.66	1.11	68.2
8574680	Baltimore, MD	0.62	1.06	71.0
8577330	Solomons Is, MD	0.65	1.11	70.8
8635750	Lewisetta, Potomac River, VA	0.85	1.26	48.2
8636580	Windmill Pt, VA	0.85	1.16	36.5
8638863	Chesapeake Bay Bridge Tunnel, VA	1.30	1.33	2.3
Root-mean-square error of predicted peak water level / mean measured peak water level = 16.1%.				

Table 8. Comparison of data and calculated peak water levels during Isabel (September, 2003).

Station No.	Station Name	Data (m)	Model (m)	Percent Error (%)
8551910	Reedy Pt, C&D Canal, DE	1.75	1.69	-3.4
8557380	Lewes, Ft. Miles, DE	1.31	1.00	-23.7
8571892	Cambridge, Choptank River, MD	1.58	1.68	6.3
8573927	Chesapeake City, MD	2.18	1.94	-11.0
8574680	Baltimore, MD	2.24	2.28	1.8
8575512	US Naval Academy, MD	1.98	2.30	16.2
8577330	Solomons Is, MD	1.85	1.80	-2.7
8632200	Kiptopeke Beach, VA	1.55	1.70	9.7
8635750	Lewisetta, Potomac River, VA	1.44	1.53	6.3
8636580	Windmill Pt, VA	1.48	1.30	-12.2
8638610	Sewells Pt, VA	1.99	2.35	18.1
8638863	Chesapeake Bay Bridge Tunnel, VA	1.87	1.91	2.1
Root-mean-square error of predicted peak water level / mean measured peak water level = 11.1%.				

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